The
Meteorological Magazine

November 1992
Vol. 121 No. 1444

METEOROLOGICAL OFFICE
11 JAN 1993
LIBRARY

551.5(09):551.507.352

A short history of the Meteorological Research Flight (MRF) 1942–92

W.T. Roach
AD Met O(MRF) 1985–88

Summary

A brief history of meteorological observations in the free atmosphere from the 17th century to the beginning of World War II is followed by an account of the events leading to the formation of MRF. Then follows the main part of the paper which consists of an account of the work (scientific, observational and airborne meteorological sensor development) of MRF during the period 1942–92, how this work was integrated with the research programme of the Meteorological Office, and of national and international collaboration with universities and other research institutions in major field experiments.

1. Before MRF

Reports of the sporadic use of kites and balloons to make meteorological measurements in the free atmosphere appear in the literature back to the mid-eighteenth century. From then until the birth of aviation in the first decade of this century, highlights were:

(a) The first manned balloon flight to measure temperature, humidity and pressure was made by an English gentleman called Jeffries in 1784, who reached an altitude of about 3 km.

(b) About 1862, Glaisher and Coxwell made similar measurements from an open gondola on several balloon flights, once attaining nearly 9 km, and nearly losing their lives in the process.

(c) During the period 1898–1904, the French investigator, Teisserenc de Bort, made nearly 600 unmanned balloon ascents to measure temperature up to 14 km. His painstaking analysis of his measurements led to the discovery of the stratosphere. These flights were the first serious meteorological research, rather than reconnaissance, flights.

As early as 1913, Shaw (then Director of the Meteorological Office) realized the potential of the aircraft as a platform for meteorological measurements and research, and suggested mounting vanes on aircraft to measure vertical air motion, and an accelerometer to measure 'bumpiness', as well as 'other meteorological measurements' including atmospheric electricity. The technology, funds and resources were not available then, or for some time afterwards, to give Shaw's proposals practical effect. Between the wars, limited attempts to fit some basic instruments to a few aircraft were made and, in 1927, a meteorological reconnaissance flight was established at Duxford, but little of meteorological value came from these initiatives.

However, the weather dependence of aviation had, from the beginning, created a demand for meteorological reporting and forecasting services, and resulted in 1920 in the absorption by the Air Ministry of the Meteorological Office. In addition, the rapid technical development of aircraft, forced by the operational demands of two world wars, had soon revealed further weather-related hazards (e.g. airframe icing, visibility of aircraft contrails to enemy aircraft, fog) which created a requirement for applied meteorological research.

During the first two years of World War II, it soon became apparent that the (still) rudimentary state of forecasting science, exacerbated by the lack of observations from the Atlantic Ocean — the source of most of our

weather — was inadequate for aircraft operations in war. The need to mitigate this situation led to two initiatives:

(a) The formation of duty meteorological reconnaissance flights at RAF stations all over the United Kingdom. By about 1942, one, two, or three flights were being made daily from up to 40 stations to observe temperature, humidity, winds, cloud amount, base and top height, to heights of up to 6 km. These observations formed an essential supplement to the standard synoptic observation network. Some 20 000 flights were made in all. Recently, this data was put into computer-compatible form and used to assist the helicopter icing problem.

(b) The formation of the Meteorological Research Committee (MRC) in November 1941 with an urgent brief to foster and oversee investigation and research into meteorological science.

One of the first initiatives of the MRC was to arrange (through the Air Ministry) for the deployment of meteorologists, led by Dr A.W. Brewer, to the High Altitude Flight (HAF) at Boscombe Down in August 1942 to investigate the atmospheric conditions favouring the formation of aircraft contrails.

2. Boscombe Down (1942–46)

At Boscombe Down, Brewer's group were initially allocated two Boston and one Spitfire aircraft on which to install their instrumentation. Soon afterwards, Fortress, Mosquito and Hudson aircraft were added. (At that time, aircraft were easier to obtain than staff!) Flying in these early aircraft, often without cabin pressurization or heating, was arduous and tiring. However, the Mosquito was better liked; pilot and meteorological observer sat cosily side-by-side in the aircraft cabin and cooperated very effectively.

The first task was to develop and install aircraft instrumentation for measuring temperature and humidity:

Temperature. A remote reading resistance thermometer was developed for temperature measurements from a Spitfire aircraft. Radiation shielding of the thermometer element, and calibrations to determine the correction required for kinetic heating of the element when exposed to airflows of up to 200 m s^{-1} enabled an accuracy of better than ± 1 °C to be attained. These thermometers were later installed on all MRF aircraft.

Humidity. The frost-point hygrometer for humidity measurements depended on noting the temperature at which frost could first be seen (by a met. observer) forming on a 'thimble' of black glass cooled by liquid nitrogen while exposed to the external airflow. This device was developed by Brewer's group and first flown successfully in a Fortress aircraft late in 1943.

With these basic instruments, it was found that the upper troposphere was quite often supersaturated with respect to ice — conditions which favoured the formation of dense, persistent contrails — and that the stratosphere was extremely dry. These results led to a practical aircraft-contrail forecasting method, but was also a scientific discovery of major importance to studies of the atmospheric general circulation and the related distribution of water vapour as a tracer of atmospheric motion.

3. MRF — The early period (1946–62)

3.1 Move to Farnborough

Following the end of World War II, the practical and scientific success of the meteorological section of the HAF at Boscombe Down led to the establishment in 1946 of the Meteorological Research Flight at the Royal Aircraft Establishment (RAE), Farnborough with the main task of advancing meteorological science, but continuing to provide advice as required on weather-related problems of aircraft design and operation. Although MRF was not so called until 1946, its work was a continuation of HAF work, and so MRF is generally considered to have begun its work in 1942.

MRF commenced with establishment for a larger scientific staff, two Mosquito and two Halifax aircraft and RAF aircrew. Fairly early in the period, these aircraft were replaced by Hastings, Varsity and (in 1952) Canberra aircraft. The Canberra could be 'nursed' to 15 km under favourable conditions, and complemented the lower-level work of the other aircraft. MRF staff and aircrew were accommodated in 'temporary' prefabricated huts near the RAE control tower until 1961, when they moved into a purpose-built brick building on the other side of the airfield.

The aircraft were serviced by the RAE, who also designed the installation of meteorological instrumentation on aircraft to ensure that military safety standards were met, and provided (from various departments) invaluable technical advice on a wide variety of topics. The crucial role played by the RAF aircrew during the whole life of MRF cannot be overstated. A posting to MRF from a 'standard' RAF station was a 'cultural shock' to some aircrew, but they soon entered into the work, and educated the scientists into what flight plans were possible under the increasingly severe navigational constraints imposed by outside military and civil aviation interests.

The daily operational schedule began (subject to aircraft availability) with a briefing meeting at 0830 UTC (often earlier) at which final flight plans for the day were decided on the basis of the meteorological situation provided by the forecasting office based (until recently) at RAE. A flight-liaison officer liaised between scientific users, MRF technical staff, RAF aircrews and several departments of the RAE in relation to flight planning and briefing, and installation and removal of scientific equipment from the aircraft. Finally, he coordinated overseas detachments, where effective liaison with a host airfield staff unfamiliar with the special demands of MRF was essential for the success of a detachment.

This organizational set-up has remained unchanged in fundamentals to this day, though naturally there has been

a great increase since 1946 in the sophistication of scientific equipment and data-processing, and also in the lead time required to design and install new equipment on aircraft.

Although aircraft have been used for meteorological research in other countries (particularly in America) since the end of World War II, the MRF facility is unique — as far as the author is aware — in having an aircraft and aircrew dedicated to it full-time.

3.2 Scientific work

The emphasis of 'in house' MRF research was (and still is) on physical rather than dynamical meteorology — i.e. with the structure and behaviour of weather on a fairly local scale, rather than the large-scale atmospheric circulation which carries, and, to some extent creates, weather. Under the active direction of Dr Murgatroyd, three main topics characterized the work of this period: aerosol and cloud physics, radiative transfer and atmospheric tracers.

3.2.1 Aerosol and cloud physics

This was a period of active development of sensors (with considerable assistance from the RAE) to measure the physical properties of clouds — e.g. the distribution of liquid water content, cloud- and rain-drop sizes, and ice particles — and of associated cloud condensation nuclei.

Sensors used then were: impaction on aluminium foil to detect ice particles and drizzle droplets, oiled slides to collect cloud droplets, hot-wire devices to measure cloud water content and a (Pollak) total aerosol counter. Data had to be manually processed which was very slow and time-consuming, but nevertheless produced some valuable studies. The emphasis was on rain-producing clouds, particularly cumulus in various stages of development, but some studies of clouds associated with atmospheric fronts, and also layer clouds were made. This work was to some extent complementary to laboratory studies of cloud microphysics being made at that time under B.J. Mason at Imperial College, and all contributed to a better understanding of the generation of precipitation, and the role of ice particles in this.

3.2.2 Radiative Transfer

Brewer and Houghton (University of Oxford) flew an infrared radiometer from the MRF Mosquito aircraft in 1954 to make some of the earliest measurements of longwave radiative fluxes and heating rates through the troposphere. So began a long tradition of the use of MRF facilities by Oxford to fly radiometers developed in the Clarendon Laboratory. Later, the installation of photometers and solarimeters on MRF aircraft were used to measure upward and downward solar fluxes in cloud and clear air. The infrared absorption properties of liquid water and water vapour were already known, but MRF flights gave some of the earliest indications of significant additional absorption of solar radiation in clouds and clear air, attributed to the presence of aerosol, particularly downstream of urban areas.

3.2.3 Atmospheric Tracers

During the period covered by this section, first under Dr R. Frith, and then under Dr R.J. Murgatroyd, much further use was made of the frost-point hygrometer and, late in the period, of an ozone detector (also developed by Brewer in the Clarendon Laboratory, University of Oxford) to study the distribution of water vapour and ozone in the upper troposphere and lower stratosphere, particularly through jet streams, and also through a range of latitudes from 10° S to 75° N. A related study was of the incidence of cirrus cloud at high levels, particularly in the easterly jet stream outflow from the Indian monsoon spreading over equatorial Africa during summer.

This topic departed from the mainstream of MRF research in that it was relevant to studies of the stratospheric–tropospheric interchange of air associated with large-scale vertical circulations in temperate and subtropical jet streams in relation to the movement of radioactive products of nuclear tests during the period. The relatively quiescent mid stratosphere was identified as a 'storage tank' for these products.

3.3 Collaborative projects

While the research outlined above was carried out largely 'in-house', it was realized that the exploitation of the data-gathering potential of the aircraft required continued development of airborne sensors and of associated data-processing; of more staff to handle this development; and (perhaps most importantly) the involvement of other research groups. Consequently, collaborative projects became an increasingly important feature of MRF work during this (early) period. Examples were: Observations of the structure of jet streams and fronts in collaboration with the Meteorological Office Forecasting Research Dept., discharge of smoke puffs and radar-reflecting foil for short-period wind investigations at the Meteorological Office radar station, sampling particle plumes for medium-range dispersion studies at the Meteorological Office research outstation at Porton Down in collaboration with the Chemical Defence Experimental Establishment there, carrying radioactive particle samplers, providing solar radiation observations for Kew Observatory, and obtaining samples of airborne pollen for Rothamsted Experimental Station. In addition, links with university research groups were strengthened and many smaller projects undertaken.

The high-altitude work of MRF was interrupted in February 1962 by the loss of the Canberra aircraft (but, miraculously, none of its aircrew) in the sea when approaching to land at Leuchars, Scotland after a long flight to measure water vapour and ozone distribution in the lower Arctic stratosphere. This work was recommenced in the following year with a replacement Canberra with improved instrumentation.

4. The Middle Period (1962–81)

This period marked a transition from the early period with several aircraft, few staff and limited resources to the modern period with advanced technological support and a much larger staff. The work was more integrated within broader research projects.

The rapid advances in microchip and computer technology in this period greatly increased the potential for instrument development on one hand, and for the modelling of atmospheric physical and dynamical processes on the other hand. In particular, the increasing speed and capacity of computers enabled the incorporation of (usually parametrized) physical processes into numerical forecasting and general circulation models, and towards the end of the period, into climate models. MRF therefore had an increasingly significant role to play in providing basic physical data for improving and validating the parametrization of physical processes in models.

In any case, a natural break in MRF work in 1962 was occasioned by the move of MRF to its new building, the loss of the Canberra aircraft and the departure of Dr Murgatroyd. After brief tenures by Mr Zobel and Mr Aanenson, Dr D.G. James became Head of MRF from 1971 to 1982.

External factors shaping the development of the MRF programme during this period were:

(a) Prof B.J. Mason was appointed Director-General of the Meteorological Office in 1965 and, soon afterwards, transferred his Cloud Physics Department at Imperial College with some of its staff to the Meteorological Office under Mr P. Goldsmith. This department has been the principal user of MRF facilities since then.

(b) The Meteorological Research Unit located at the Telecommunications and Radar Research Station, Malvern led (after 1966) by Dr K.A. Browning. This unit was responsible for pioneering the national weather radar network we now have, and its common areas of interest with MRF were frontal dynamics and clear air turbulence.

(c) The Meteorological Research Unit at Cardington, Bedford used the tethered balloon facility there to make measurements of the structure of the atmospheric boundary layer. This unit has collaborated with MRF in studies of boundary-layer flow and turbulence in the vicinity of hills.

(d) Growing concern with atmospheric pollution in general and the acid rain problem in particular during the 1970s led to collaboration with the Central Electricity Research Laboratories (CERL), Leatherhead and the beginning of atmospheric chemistry studies at MRF.

The Hastings and Varsity aircraft were withdrawn from MRF at the end of their design lives during the late 1960s, and replaced by another Varsity and (not until 1974) by the C-130 Hercules aircraft (XV208), or 'Snoopy' as it became known after the installation of its nose probe (Fig. 1).

The case for acquiring the C-130 rested heavily on the invitation for it to participate in the international Global Atlantic Tropical Experiment (GATE) in 1975. This was the first of about a dozen international cooperative experiments (see Annex B) in which the Hercules has participated up to now.

4.1 Instrumental development

Important developments during this middle period were:

On-board data-processing system. At the beginning of this period, aircraft data was recorded manually by observers, or on charts, and the subsequent processing was also largely manual. It had been realized for some time that a radical improvement in aircraft data-process-

Figure 1. A view of the C-130 in flight. Its capacity and endurance make it ideal for atmospheric research.

ing facilities was essential if further scientific progress was to be made. The main concept was to install an on-board computer to record data from meteorological sensors on tape to be processed after the flight by ground-based computer. This computer was installed in an observer's cabin (or van) in the Hercules. This cabin protected observers in it from aircraft noise, provided real-time displays in the van and to the aircraft scientist on the flight deck, while the van itself could be removed bodily from the aircraft during periods of major servicing.

The implementation of this system was given urgency by the planned participation of the Hercules in GATE. Aircraft data had to be transferred to magnetic tape in a prescribed format for transmission to other scientific institutions involved in GATE.

A parallel development was a move away from dependence on the RAE for ground-based computer processing of data with the installation of computer systems in MRF, and virtually complete independence from RAE computing facilities was achieved by about 1980.

Inertial navigation. The installation, first on the Canberra and later on the C-130, of nose probes carrying rapid-response wind vanes linked to inertial platforms centred near the aircraft centre of gravity, made it possible to extract the aircraft position at any time, and also wind and turbulence data from which aircraft motions had been automatically removed. This development was foreseen by Shaw 60 years before.

Dropsondes. One of the first tasks undertaken by the Cloud Physics Department after its move to the Meteorologcal Office was to develop a radiosonde to be released from the Hastings aircraft. The transmitted data would then be received and stored by an on-board computer. This system was used on the Varsity aircraft in Project SCILLONIA (see below) in 1969–70. A radically improved system was then developed for installation on the C-130, and eventually used in a major project in 1987.

Cloud-physics probes. During the first decade of this period, it became possible to collect and process large amounts of cloud microphysical data in a reasonable time using advanced optical-sensing techniques developed in particular by Knollenberg, an American electronics engineer. Some of his optical probes were purchased by the Cloud Physics Dept. and installed on the C-130. They depended mainly on detecting and measuring the intensity of pulses of light scattered from cloud droplets (and later precipitation and ice particles) passing through a sensitive volume exposed to the airflow. An example of the data obtained using these probes is shown in Fig. 2.

A holographic camera was also installed to give the 'instantaneous' location and size of particles in a 0.5 litre air sample 'caught' by a laser pulse a few nanoseconds in duration. Liquid water content was measured by an advanced hot-wire device and compared with liquid water contents derived by summing over drop-size distributions obtained with the Knollenberg probes. There remained, however, considerable difficulties in assessing how representative the measurements were of the structure of cloud volumes large compared with the (very small) sampling volume of the probes.

Chemical sampling. A range of chemical sampling equipment was installed on the C-130 for use by CERL. These enabled both *in situ* measurements to be made,

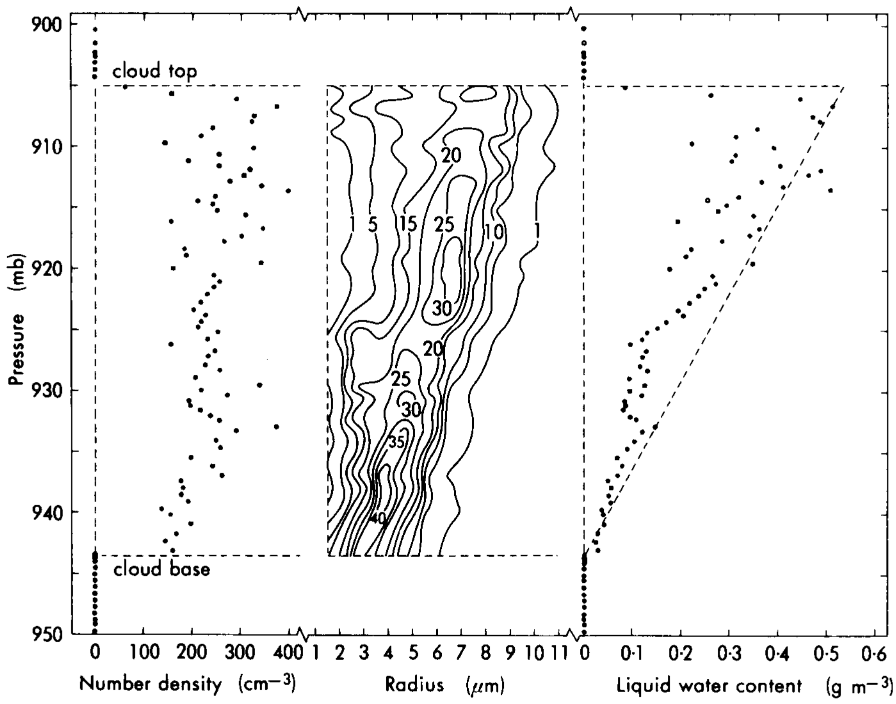

Figure 2. Profiles of the concentration and spectra of cloud droplets, and of the liquid water content through a layer of stratocumulus cloud on 19 November 1976 using an optical probe.

and samples collected for later analysis of several chemical species, particularly nitrogen and sulphur species and ozone.

4.2 Scientific work

Cloud Physics. Early in this period, the main thrust of research in cloud physics was moving away from laboratory studies and towards the interaction of the cloud microphysics with cloud dynamics. This study could only be advanced by the use of research aircraft.

The first major project SCILLONIA (based from the Scilly Isles) used dropsondes released at 5 km from the Varsity aircraft to obtain the mesoscale structure of wind, temperature and humidity within active warm-frontal zones approaching the British Isles from the Atlantic, where the system was (as yet) undisturbed by topography. A major finding of this study was the existence of organized bands of vertical ascent and descent spaced apart by about 100 km and correlated with bands of precipitation. This led to the development of a new dynamical theory of 'conditional symmetric instability' depending for its initiation upon the release of latent heat in air ascending the frontal slope.

Atmospheric turbulence. The installation of the inertial platform on the Canberra and C-130 made possible some important studies of turbulence in various meteorological contexts:

(a) Studies of the structure of the marine boundary were made to check existing marine boundary layer similarity theory and bulk aerodynamic transfer coefficients. As part of this study, the C-130 participated in the Joint Air–Sea Interaction (JASIN) experiment off north-west Scotland in 1978.

(b) In collaboration with MRU Cardington, measurements were made from the C-130 of the flow and turbulence structure around Ailsa Craig, a steep, symmetrically shaped island off south-west Scotland. Measurements were also made with a tethered balloon deployed to Ailsa Craig. This study was used to validate a numerical model of the airflow in order to tackle the very difficult problem of airflow over hilly or mountainous terrain needed urgently to improve parametrization of frictional drag of the earth in forecasting models.

(c) Studies of the structure of high-level clear air turbulence and mountain waves were made using the Canberra aircraft with the objective of improving understanding of the role of internal friction (as distinct from friction with the ground) in modifying the atmospheric circulation. Some clear air turbulence studies were made in collaboration with MRU Malvern, with the aircraft flying over a high-power Doppler radar able to detect clear air turbulence. A detachment of the Canberra aircraft was made to the Colorado mountains in 1973 to measure the vertical transfer of momentum flux by high-level standing gravity waves. This is internal drag due to the 'cog-wheel' effect of distortions of the wave shape.

Atmospheric Chemistry. A series of flights were made over the North Sea in downwind plumes emitted by a major power station to study the dispersion and chemical evolution of plume pollutants. The rate of oxidation of sulphur dioxide to sulphate was found to depend critically on the presence of cloud.

Radiative Transfer. Work in this area was relatively low-key during this period. However, the prototype flight model of the Selective Chopper Radiometer flown on the NASA NIMBUS 5 satellite was installed on the Canberra aircraft, and a study made by the University of Oxford group of the background (continuum) absorption (attributed to water vapour) across the 10–12 micron 'window' in the atmospheric infrared spectrum. The emission associated with this absorption is a significant contributor to the greenhouse effect, but has not had the 'publicity' of carbon dioxide in this regard.

During the late 1970s, the evolution of layer clouds, and particularly their interaction with radiative transfer had begun to attract attention. Fluxes of solar and terrestrial (long-wave infrared) radiation through marine stratocumulus were observed during JASIN with radiometers mounted on the Hercules and other aircraft. In this case, the fluxes observed agreed well with those generated by radiative transfer schemes.

By the end of this middle period, MRF had an international reputation, and the C-130 was in regular demand to participate in international projects.

The Canberra aircraft (WE173) was removed as part of the cuts in Government expenditure in 1981. The ability of the Canberra aircraft to provide observations in the lower stratosphere was limited to the aircraft ceiling of about 15 km. While this had been an advance on the Mosquito aircraft ceiling of about 12 km, 15 km was not adequate for comprehensive observations within most of the ozone layer — probably the most important requirement in modern environmental studies of the stratosphere. Unfortunately, there was no opportunity in 1981 of obtaining a replacement aircraft with a sufficiently high ceiling to make worthwhile advances in many investigations of the stratosphere. Accordingly, the thrust of MRF's work became concentrated on tropospheric studies during the modern period.

5. The modern period (1981–92)

With the withdrawal of the Canberra aircraft in 1981 and the retirement of Dr James in 1982, MRF entered a slightly unsettled period in that Dr Jenkins, the present Head of MRF, became (in 1991) the seventh incumbent of that post since James departed in 1982. Nevertheless, the momentum of MRF progress was not seriously interrupted. The main initiatives taken during this period (in roughly chronological order) were:

(a) By 1981, climate research was increasing in importance. When Dr Readings took over from Dr James in 1982, he was directed to upgrade radiative transfer research at MRF in view of the significance of cloud-radiation interaction to climate research.

(b) The ground-based computer at MRF was becoming obsolescent and had to be replaced to cope with the increasing data-processing, analysis and numerical modelling work being undertaken in MRF. In addition, the capacity of recently established links with the main Meteorological Office computer system at Bracknell needed expanding. The development was successfully completed by 1988.

(c) Upgrading of the airborne data-processing system and the transcription of aircraft data tapes to the ground system had again become necessary. This had achieved an acceptable level of performance by 1989.

(d) Installation of additional sensors on the C-130 continued throughout the period in response to the research requirements detailed below. The aircraft now probably carries a larger range of meteorological sensors (Figs 3 and 4) than any other meteorological research aircraft.

(e) As part of a reorganization of the structure of the Physical Research Directorate of the Meteorological

Figure 3. The operation of the meteorological sensors is coordinated by the Aircraft Scientist from the flight deck where he has a clear view through the aircraft window and can call up a graphical display of the real-time output of any sensor as required.

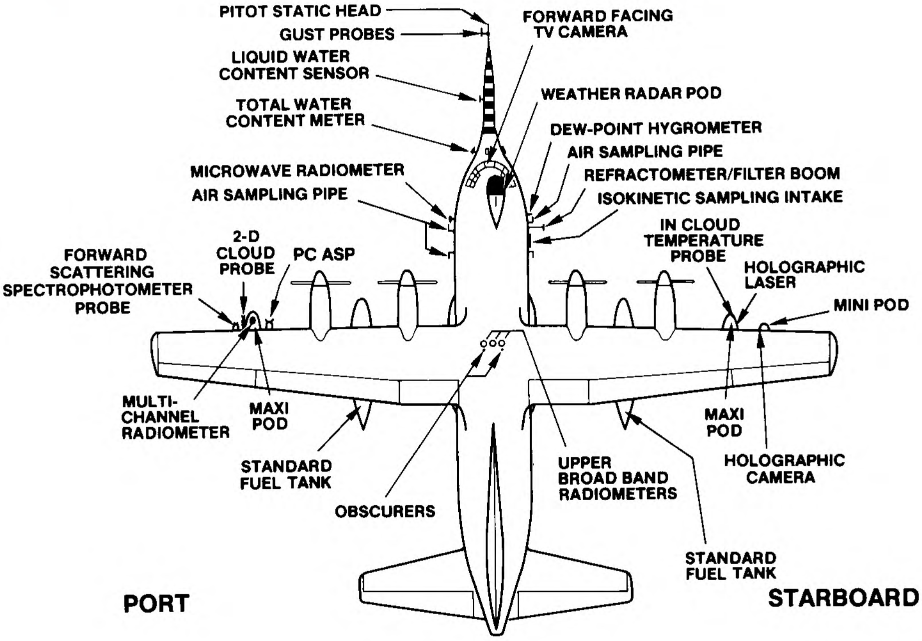

Figure 4. Plan view of the C-130, showing the location of the main meteorological sensors.

Office, the Cloud Physics Department was disbanded, but its two sections using MRF (cloud microphysics and atmospheric chemistry) were brought into the branch, but it was not until 1991 that the latter section moved to Farnborough. In addition, the advanced satellite instrumentation section of the old High Altitude Research Branch was moved to a separate unit located next to MRF, to be known as the Remote Sensing Instrumentation Branch. At the end of these moves the Meteorological Office presence at RAE had expanded from about 25 to about 75. By that time, RAE had become part of the Defence Research Agency (DRA).

Most of the work on the research topics pursued during the middle period (section 4) has continued to the present day, but with some changes of emphasis.

Radiative Transfer. Of central importance to all general circulation and climate modelling is an accurate evaluation of the contribution of radiative transfer to the distribution of heating and cooling in the atmosphere. Accordingly, the principal research objective at MRF was to obtain simultaneous measurements of the optical and physical properties of clouds and aerosol and their environment in order to improve the basis of radiative transfer schemes used in general circulation and climate models. To this end, the first few years of this period were devoted to upgrading the radiometer installations on the C-130 in the following respects:

(a) An updated version of the Oxford Selective Chopper Radiometer (SCR) — previously installed on the Canberra — was installed on the starboard wing of the C-130. This radiometer was designed to sense radiation in 16 channels distributed mainly in the atmospheric window region (10–12 microns) and the near solar infrared spectrum.

(b) Upward- and downward-facing total solar (pyranometers) and terrestrial (pyrgeometers) radiative-flux sensors and their associated data-processing were upgraded.

This equipment was operational by 1987, and the following studies made:

(a) There is a balance of evidence that the observed absorption of solar radiation in layer clouds is generally higher (particularly in the near infrared), and the albedo (reflectivity) of cloud is less than model predictions. In addition, the rate of increase of albedo with fractional cloud cover of broken cloud fields is slower than model predictions. Several theories have been advanced to account for these discrepancies, which remain unresolved. However, the observational base for this study is still inadequate. In this regard, participation of MRF in FIRE (the First International Satellite Cloud and Climatology Regional Experiment) in California in 1987 was an important step.

(b) A long-standing area of uncertainty is the cause and amount of background (continuum) absorption and emission of infrared radiation stretching across the 8–13 micron window, and is attributed to water vapour. This is about 10% in temperate latitudes, but is about 50% in tropical latitudes and is a significant contributor to the greenhouse effect. The SCR was used in a detachment to Dakar, Africa to obtain much-needed observations of the tropical continuum absorption, found to be about 30% higher than existing theoretical models. Further flights have been made around the United Kingdom and over the Mediterranean, and are being analysed.

(c) A start was made on the difficult study of cirrus cloud, limited (at MRF) by the inaccessibility of the higher cirrus cloud by the C-130. MRF participated in a European International Cirrus Experiment in 1989 in parallel with other aircraft with higher ceilings. While some rudimentary knowledge of the gross optical properties of cirrus cloud are beginning to emerge, problems of methods of measurement and their interpretation have still to be resolved, and are likely to absorb most effort in this area for some time to come.

Mesoscale Frontal Dynamics. A major collaborative field study — FRONTS 87 — with French research groups, using ground radar and aircraft deploying dropsondes (Fig. 5) was based at Brest.

The main objective was to obtain an improved dynamical understanding of synoptic — (100–1000 km), mesoscale — (30–100 km) and smaller-scale interactions within systems containing cold fronts. Some principal findings were:

(a) Thermal wind balance along a front is roughly maintained on scales greater than 50 km, but instabilities occur on smaller scales.

(b) Direct evidence of conditional symmetric instability, first thought to be associated with rain bands in warm fronts observed in SCILLONIA.

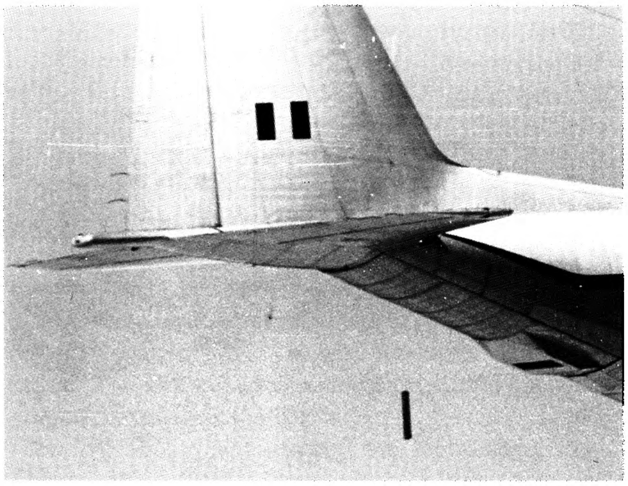

Figure 5. A dropsonde immediately after ejection from the horizontal slot to the right of the sonde. A small parachute is deployed from the sonde a few seconds after release

(c) Frontal development is significantly influenced by regions of condensation and evaporation — particularly of snow and ice particles.

(d) The importance of the role of some conservative dynamic variables (particularly potential vorticity) was clarified.

The data collected during FRONTS 87 (e.g. Fig. 6) has given a fresh impetus to the difficult study of factors controlling the mesoscale structure of fronts, and a successful follow-on study (FRONTS 92) promises to be equally rewarding.

Cloud Physics. Observations and numerical modelling of the water and heat balance of marine stratocumulus was the main theme of this period. Aspects receiving particular attention were: entrainment of dry, relatively warm air into the cloud at cloud top; interaction of the cloud evolution with radiative transfer; and the formation and precipitation of drizzle formed in thicker cloud layers. Successful field-studies were made as contributions to the programmes of FIRE and (recently) ASTEX (Atlantic Stratocumulus Transition Experiment).

A related study of nocturnal stratocumulus was also made from a tethered balloon at Cardington using some of the cloud physics probes normally operated from the C-130. Finally, some case-studies of sea fog forming in early summer off the north-east coast of Scotland were made using the C-130, and the results interpreted as an extension of a numerical model of stratocumulus cloud with its base on the sea surface. Insight into the fog as a self-maintaining, persistent system was gained.

A study was made of the microstructure of ice particles in light precipitating cloud. This involved collaboration of the C-130 with the Rutherford Appleton Laboratory using their dual polarization radar at Chilbolton Observatory. The ratio of horizontally and vertically polarization reflectivity of the cloud observed by radar was related (with some success) to the physical properties of the ice crystals observed from the C-130.

Atmospheric Turbulence. Further projects to investigate the effect of hills on airflow were made over the hills of South Wales using the C-130, tethered balloon and other surface observations. Other international projects were joined to measure the structure of organized convection over the North Sea (KONTUR) and humidity exchange over the sea.

Satellite Meteorology. MRF's involvement in aspects of satellite meteorology have expanded in two main areas; the evaluation of sensors to be installed on satellites, and the provision of ground truth measurements from the aircraft for comparison with satellite measurements at the same time in the same area (known as calibration–validation or 'cal–val' activities).

In the first area, an evaluation has been made of the microwave radiometer (AMSU-B) mounted on the C-130 to measure water-vapour emission in two wavelengths. This radiometer is due to be installed on a NOAA satellite in 1994. The MCR was used during the detachment of the C-130 to Dakar in 1987 to test the principles of the Along Track Scanning Radiometer (ATSR) developed for the ERS-1 satellite.

Cal–val activities have concentrated on the European Space Agency ERS-1 satellite launched in 1991. In September 1991, wind measurements over the sea off the west coast of Norway were made to validate wind algorithms derived from ERS-1 scatterometer data (Fig. 7).

Shortly afterwards, measurements of sea surface temperature (SST) were made from the C-130 in the South Atlantic for comparison with ATSR. (This detachment also provided measurements of the effect of diffuse and direct solar radiation on the dust veil from Mt Pinatubo.)

Atmospheric Chemistry. Although work on 'acid rain' is no longer a major topic (however, sulphur dioxide plumes are still tracked to compare against the

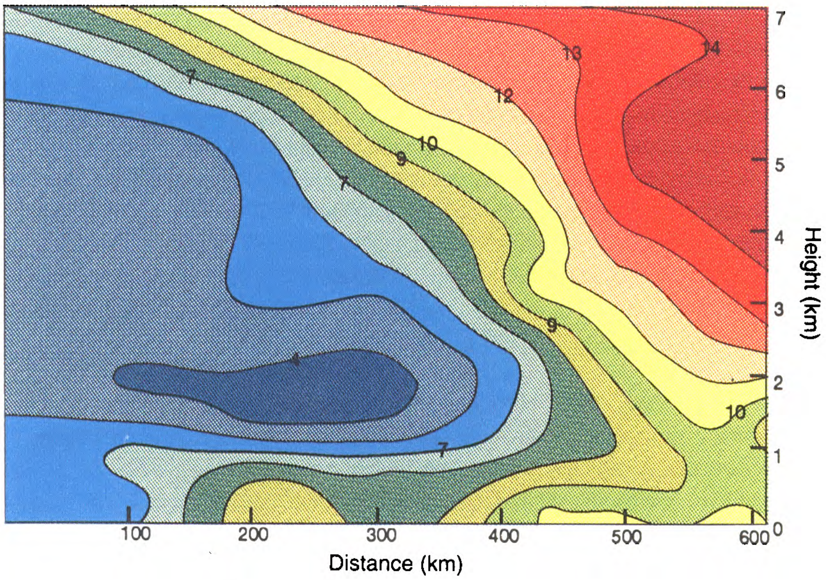

Figure 6. A cross-section of a cold front from FRONTS 87 revealing the fine details of humidity (as wet-bulb potential temperature in °C).

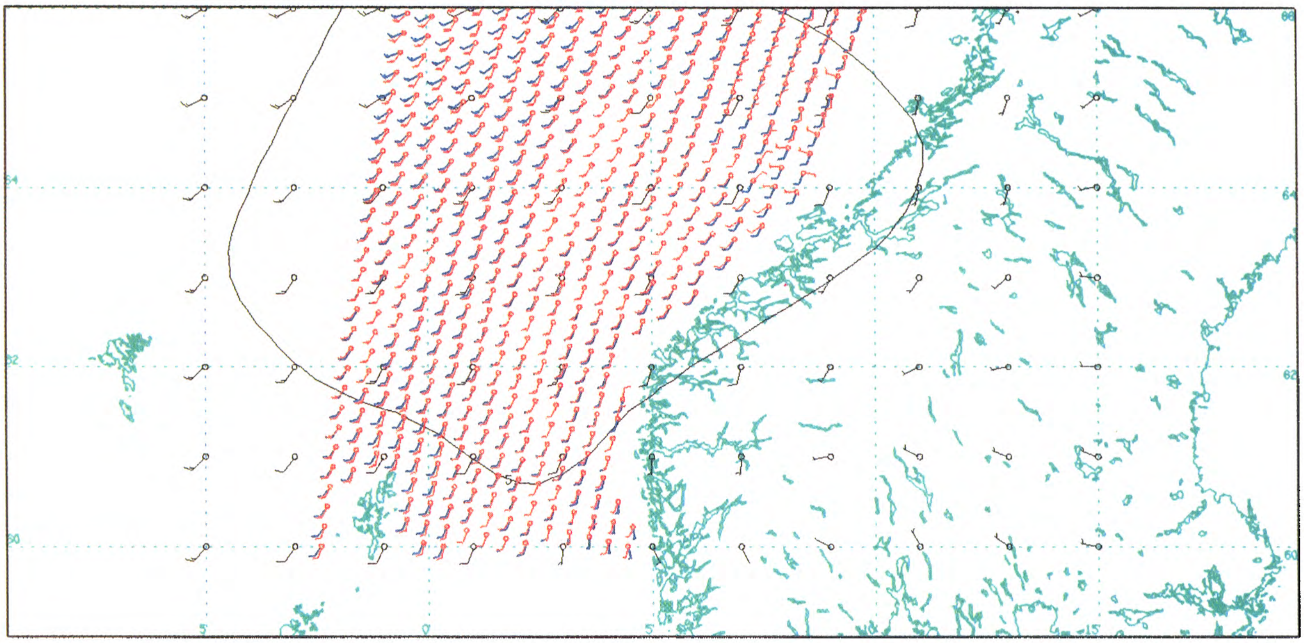

Figure 7. Low-level winds (black vectors) measured from the C-130 off the Norwegian coast are compared with those (red vectors) derived from the scatterometer on the ERS-1 satellite.

predictions of the Met. Office's Nuclear Accident Model), other areas of atmospheric chemistry have expanded. The increasing concentration of ozone in the troposphere, and the realization of its importance as a 'greenhouse' gas has highlighted the need to understand its generation from pollutants such as nitrogen oxides, hydrocarbons and carbon monoxide. The contribution from the stratosphere is also not well known. By 1990, a wide range of chemical samplers had been installed on the C-130 in conjunction with the University of East Anglia and KFA Julich in Germany to tackle this problem.

The chemical instrumentation was brought into use in an unexpected way in March 1991 after the Gulf War had left several hundred oil wells alight in Kuwait. Model calculations that the environmental impact would be locally severe but regionally and globally insignificant were supported by the first airborne measurements made by MRF of chemical and radiative properties of the smoke plume a few weeks after the end of the war. US and German aircraft followed shortly after.

6. The future

Following a major service in 1992, the C-130 has a very full diary for the following two years, with involvement in international programmes in air–sea interaction (TOGA-COARE), atmospheric chemistry (OCTA and NARE) and clouds and radiation (EUCREX). NERC has established a post of Aircraft Officer at MRF in order to enhance the use of the C-130 by the university community in collaborative research programmes with MRF.

There is little doubt that the requirement for a platform for *in situ* measurements of atmospheric processes will continue for the foreseeable future, although the particular emphasis will change. Although weather forecasting and climate prediction models can be improved by greater time and space resolution, this must be accompanied by a better representation of physical processes, many of which are still poorly understood. The main task of MRF continues to be the execution of basic research of atmospheric processes and publication of the results, but with increasing emphasis on the timely incorporation of the results into atmospheric models. In addition, the need for satellite instrumentation development, with the subsequent validation of space-borne measurements, is likely to expand as a greater proportion of global data comes from satellites.

Finally, following the announcement in 1991 that routine military flying will cease from the Farnborough airfield in 1995, hard decisions will have to be made about the future location of MRF. A return to the MRF birthplace at Boscombe Down is one possibility.

Acknowledgements

The author is indebted to Dr G.J. Jenkins, Head of Meteorological Research Flight, for his cooperation, and for contributing sections 5 and 6, photographs and Annexes of this paper. The author also thanks Dr A.W. Brewer and Dr R.J. Murgatroyd for their comments on, and suggested additions to, a draft of this paper.

ANNEX A

Aircraft of the Meteorological Research Flight

2 x Spitfire + Boston (original establishment)
Hudson
Flying Fortress
Mosquito

Mosquito	VL621
Mosquito	RG248
Halifax	ST817
Halifax	ST796
Hastings	TG618
Hastings	TG619
Canberra B2	WJ582
Varsity	WJ906
Canberra PR7	WE173
Varsity	WF425
Hercules	XV208

Assistant Directors Meteorological Office (Meteorological Research Flight)

1942	Dr A.W. Brewer
1946	Dr R. Erith
1951	Mr H.C. Shelland*
1951	Dr R.J. Murgatroyd
1962	Mr R.F. Zobel
1967	Mr C.J.M. Aanensen
1971	Dr D.G. James
1982	Dr C.J. Readings
1984	Dr R. Pettifer
1985	Dr W.T. Roach
1988	Dr P. Jonas
1989	Dr S. Mattingly
1990	Mr W.D.N. Jackson*
1991	Dr G.J. Jenkins

* Acting Heads between main appointments

Officers Commanding Meteorological Research Flight

1948	Flt Lt Tomlinson
1952	Flt Lt N.C. Thorne
1953	Flt Lt H. Baker
1955	Flt Lt S.F. Thomas
1958	Flt Lt D.A. Cree
1962	Flt Lt A. Abczynski
1966	Flt Lt G.F. Holbrook
1969	Sqn Ldr G.F. Holbrook
1970	Sqn Ldr N. Lamb
1977	Sqn Ldr M.J. Bibby
1980	Sqn Ldr M.K. Allport
1983	Sqn Ldr M.J. Stokes
1985	Sqn Ldr D. Curteis
1988	Sqn Ldr S.R. Roberson
1991	Sqn Ldr M. Lampitt
1992	Sqn Ldr H. Burgoyne

ANNEX B

Aircraft campaigns and detachments

Year	Aircraft	Base	Projects
1952	Canberra	Khartoum	Humidity
1957		Malta	Latitudinal
		Nairobi	variations of temperature
1960		Nairobi	and humidity
1961		Malta	at high levels
1962		Bodø	Ozone also measured after 1959
1965	Canberra	Singapore	Vertical extent of Cb
1970	Canberra	Malta	Sea surface temperture
1970	Varsity	St Mawgan	SCILLONIA: warm fronts
1973	Canberra	Denver	WAMFLEX: mountain waves
1974	Hercules	Dakar	GATE: tropical convection
1975	Canberra	Dakar	Tropical radiation
1978	Hercules	Gibraltar	measurements for satellites
1979		Dakar	and air sampling
1977–80	Canberra	Lossiemouth	Lat/Seasonal humidity cross-sections
1978	Hercules	Machrihanish	JASIN: air–sea interaction
1978		Gibraltar	Meteosat
1979		Dakar	Meteosat
1980		Gibraltar	Mount St Helens volcanic dust sampling
1981		Europe	KONTUR: turbulence over the sea
1983		Bermuda	CAMEX: microwave sounding trials
1983		Machrihanish	NARTHEX: frontal structure
1985		Bodø	PLEXUS: polar lows
1987		Farnborough	HEXOS: humidity over the sea
1987		San Diego	FIRE: marine stratocumulus
1987		Farnborough	FRONTS87: frontal dynamics
1988		Dakar	WATER: water vapour continuum
1989		Farnborough	ICE89: International Cirrus Experiment
1990		Trondheim	ERS-1 instrument development
1990		Oulu	SAAMEX: microwave
1990		Crete	MASTEX: water vapour continuum
1991		Farnborough	TOASTE: strat–trop exchange
1991		Bahrain	GULFEX: Kuwait oil smoke plume
1991		Farnborough	CHEMEX: atmospheric chemistry
1991		Trondheim	RENE1: ERS-1 winds comparison
1991		Ascension Is	FATE: ERS-1 SST comparison
1991		Trondheim	RENE2: ERS-1 winds comparison
1992		Farnborough	FRONTS92: cold front waves
1992		Azores	ASTEX: marine stratocumulus